OXYGEN INTAKE IN TRACK AND TREADMILL RUNNING WITH OBSERVATIONS ON THE EFFECT OF AIR RESISTANCE

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SUMMARY

1. The relation of $\dot{V}_{O_2}$ and speed was measured on seven athletes running on a cinder track and an all-weather track. The results were compared with similar observations on four athletes running on a treadmill.

2. In treadmill running the relation was linear and the zero intercept coincided with resting $\dot{V}_{O_2}$.

3. In track running the relation was curvilinear, but was adequately represented by a linear regression over a range of speeds extending from 8·0 km/hr (2·2 m/sec) to 21·5 km/hr (6·0 m/sec). The slope of this line was substantially steeper than the regression line slope for treadmill running.

4. The influence of air resistance in running was estimated from measurements of $\dot{V}_{O_2}$ on a subject running on a treadmill at constant speed against wind of varying velocity.

5. The extra O_2 intake ($\Delta \dot{V}_{O_2}$) associated with wind increased as the square of wind velocity. If wind velocity and running velocity are equal, as in running on a track in calm air, $\Delta \dot{V}_{O_2}$ will increase as the cube of velocity.

6. It was estimated that the energy cost of overcoming air resistance in track running is about 8 % of total energy cost at 21·5 km/hr (5000 m races) and 16 % for sprinting 100 m in 10·0 sec.

INTRODUCTION

The first detailed study of the relation of oxygen consumption and speed in running was that of Sargent (1926). Sargent solved the difficulties associated with the bag method by having his subjects run 120 yd. holding their breath. Expired gas was collected for 40 min after running, and the resting supine O_2 intake was deducted from the total O_2 intake to give the O_2 consumption, and hence the energy requirement of the work. The results seemed to show that the O_2 consumption in l./min increased as the

3·8th power of velocity. Sargent's (1926) findings, although widely accepted over the next 40 years, were challenged by Margaria (1938), who claimed that the power developed in running was greatly over-estimated by Sargent's (1926) method, and that the energy requirement was a linear function of speed. Asmussen (1946) and Christensen & Hogberg (1950a, b), showed that the aerobic equivalent of the O_2 debt was only about half that of concurrently absorbed O_2. More recently, Margaria, Cerretelli, di Prampero, Massari & Torelli (1963) and Margaria, Cerretelli & Mangili (1964) have shown, from measurements of O_2 intake and estimates of whole body lactate and pyruvate, that the straight line representing the relation between energy requirement and speed in continuous running can be extrapolated to give the energy requirement at speeds above that corresponding to the maximum O_2 intake; hence the energy requirement of running per metre of distance run is constant and independent of velocity apart from possible variation in efficiency at sprint speeds.

Investigations of running since the 1920's have been carried out with few exceptions on the treadmill, which differs from track running in that no work is done in overcoming air resistance. Du Bois-Reymond (1925) and Hill (1927) investigated the question of air resistance by measuring the pressure exerted on models at varying air velocities, and obtained closely similar results. Hill (1927) concluded that the force exerted by a runner against air resistance varied with air density, the projected area of the runner, and the square of velocity, and that air resistance accounted for 3–5 % of the total energy requirement. However, if the energy requirement of running varies directly with speed and not as the 3·8th power, then the percentage of the total energy used in overcoming air resistance will be a much larger fraction of the total energy expenditure than that which Hill (1927) envisaged. This seems the most likely explanation of the unexpectedly high speeds recorded in races over short distances at altitude, where air resistance is reduced (Table 3).

The investigation herein reported was undertaken primarily to determine the relation of O_2 intake and speed for athletes on the running track, as it seemed clear from the above considerations that the treadmill relation was not valid for track running. The results were compared with data collected on other athletes on the treadmill, and a climatic-chamber experiment was carried out to confirm that the differences observed are mainly attributable to wind resistance.

METHODS

Track experiments. The track experiments were conducted on a cinder track and an all-weather track. The athletes taking part (Table 1) performed their usual warm-up consisting of 10–20 min of slow running, and were given suitable practice with the

apparatus. The experimental procedure consisted of running two to four timed laps at a constant speed, with collection of expired gas on the last lap. The gas collection was started after approximately 3 min of running at each speed, 150–200 l. of gas being collected. Each athlete performed a series of two to five runs at different speeds. Speeds were increased step-wise, and some athletes rested for a few minutes before the final mile. Speeds were calculated as the average times for two to four laps.

The method of collecting expired gas was as follows. A vehicle containing the apparatus was driven alongside the runner. A low-resistance valve unit, connected by 25 mm i.d. tubing to a 300 l. bag, was suspended in front of the runner's face by means of a 3 m pole extending from the vehicle. Before the final lap the runner put on a nose clip and placed the mouth-piece between his teeth, taking care to keep his lips closed round it. The athlete ran about 1 m from the side of the vehicle and level with the wind-screen.

The bags were emptied through a dry gas-meter, the calibration of which had been recently checked. Duplicate gas samples were collected in soda-glass ampoules for subsequent analysis in duplicate on a Lloyd gas-analyser (Lloyd, 1958).

Treadmill experiments. The treadmill results were collected at Font Romeu (1800 m), France, with similar apparatus. In these experiments, which were concerned with temperature regulation, the subjects ran continuously for periods up to an hour on different days.

Effect of wind. An experiment was carried out in the climatic chamber at the Institute of Aviation Medicine, Farnborough, in which one of the athletes taking part in the above investigation, M. Turner, ran on a treadmill at a constant speed of 15·9 km/hr (4·42 m/sec) facing winds of various velocities measured with a cup anemometer and a vane anemometer. The readings agreed substantially with the fan-speed calibration. Control measurements of O_2 intake at zero wind velocity were begun after 10 min of running, expired gas being collected over 5 min. The wind velocity was then raised at 10 min intervals from zero to 42 km/hr (11·67 m/sec), expired gas being collected over the last 3 min at each wind velocity. After a 2 hr pause, observations were made at wind velocities of 36 km/hr (10·0 m/sec) and 66 km/hr (18·3 m/sec) following a preliminary 15 min run at zero wind velocity. Ambient temperature throughout was 21·5° C. The projected surface area of the runner was estimated from a photograph of the subject running on the treadmill beside a rectangular surface of known area.

RESULTS

Oxygen intake ($\dot{V}_{O_2}$) and speed. Figures 1 and 2 contain results collected on seven athletes on the track and on four athletes on the treadmill. Particulars of the subjects are given in Table 1. Each plotted value represents a single determination of $\dot{V}_{O_2}$. Regression lines were fitted by the method of least squares. In treadmill running the relation of $\dot{V}_{O_2}$ and speed was similar to that found by Margaria, Cerretelli, Aghemo & Sassi (1963) on two Olympic athletes. The energy cost per metre of distance run was 0·95 cal/kg compared with the value of 1 cal/kg given by those authors. The intercept with the ordinate had a value approximating to resting $\dot{V}_{O_2}$, as Margaria and his associates (1963) found. The line representing results collected on the running track had a steeper slope than the treadmill line, and the $\dot{V}_{O_2}$ at a speed of 21·5 km/hr (6·0 m/sec), which approaches

the speed of a 5000 m race, was 6·3 ml./kg.min higher than $\dot{V}_{O_2}$ at the same speed on the treadmill, the respective values being 74·6 ml./kg.min compared with 68·3 ml./kg.min.

TABLE 1. Particulars of the subjects

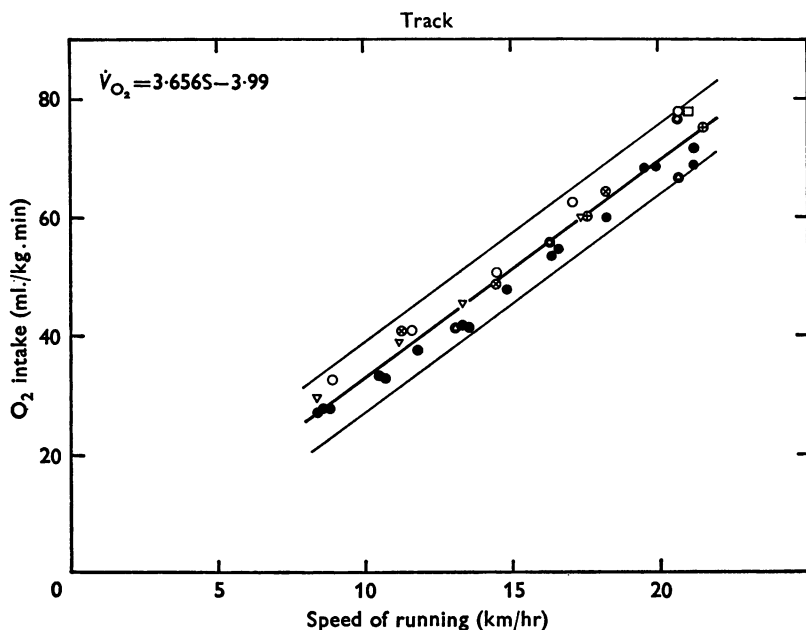| Name	Age (yr)	Height (cm)	Weight (kg)	Expt.
Fogg, C.	33	182	74·3	Treadmill
Holt, R.	23	180	62·8	Treadmill
Hyman, M.	34	177	63·6	Track
Johnston, T.	26	174	59·9	Track and treadmill
North, G.	30	169	53·8	Track
Stewart, C.	21	173	54·1	Track
Thresher, J.	27	179	65·8	Track
Tulloh. B.	31	171	53·6	Track
Turner, M.	28	180	65·0*	Track and treadmill
Means	28	176	61·4	

* 66·1 kg in wind tunnel experiments.

Fig. 1. Relation between O_2 intake and running speed on a cinder track and an all-weather track. 95% confidence limits are shown. Subjects were: ⊙ B. T., ◉ G. N., ⊗ M. H., ⊕ C. S., ◿ M. T. (cinder track) and ● B. T., ○ G. N., ▽ J. T., □ T. J. (all-weather track).

Examples of individual graphs are shown in Fig. 3. In two athletes running on the treadmill the $\dot{V}_{O_2}$/speed relation was linear, and in two it was non-linear. In the case of track running, all the graphs were non-linear.

B. Tulloh, who normally runs barefoot, ran both in shoes and barefoot on the all-weather track. There was remarkably little difference between the results in spite of the fact that the shoes weighed 250 g each. There was no significant difference between results obtained on the cinder track and the all-weather track. The variation in lap times at high running speed, and other data relating to performance, are shown in Table 2. It is seen that $\dot{V}_{O_2,max}$ was reached by some athletes but not others. In three athletes, for whom satisfactory data are available, $\dot{V}_{O_2,\,max}$ was 77–78 ml./kg.min. Comparable values have been reported by Saltin & Åstrand (1967). The highest value reported by those authors was 82 ml./kg.min for K. Keino, at that time the world record holder over 5000 m.
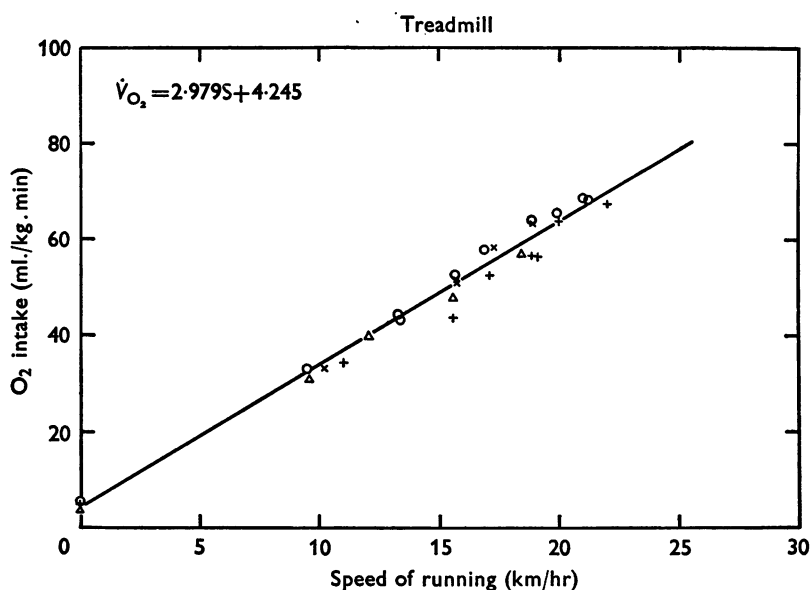

Fig. 2. Relation between O_2 intake and speed for athletes running on a treadmill. Subjects were: × M. T., ○ R. H., + T. J. and △ C. F.

Effect of wind. The mean value of $\dot{V}_{O_2}$ for running at 15·9 km/hr (4·42 m/sec) without wind was 2·924 l./min. The $\dot{V}_{O_2}$ at the same speed of running, in the presence of wind, varied from 3·089 l./min at a wind velocity of 16·2 km/hr (4·50 m/sec) to 4·960 l./min at a wind velocity of 66 km/hr (18·3 m/sec). The projected area (A_p) determined from a photograph, which is reproduced in Fig. 4 to show the exact position of the limbs, was 0·478 m². The ratio of projected area to surface area was

$$0.478/1.80 = 0.266.$$

In Fig. 5 $\dot{V}_{O_2}$ in l./min has been plotted against the square of the wind velocity (V^2) which is expressed in m/sec as being the most convenient unit for this purpose. The equation of the graph is

$$\dot{V}_{O_2} = 0{\cdot}0089\ V^2 + 2{\cdot}85 \tag{1}$$

so that

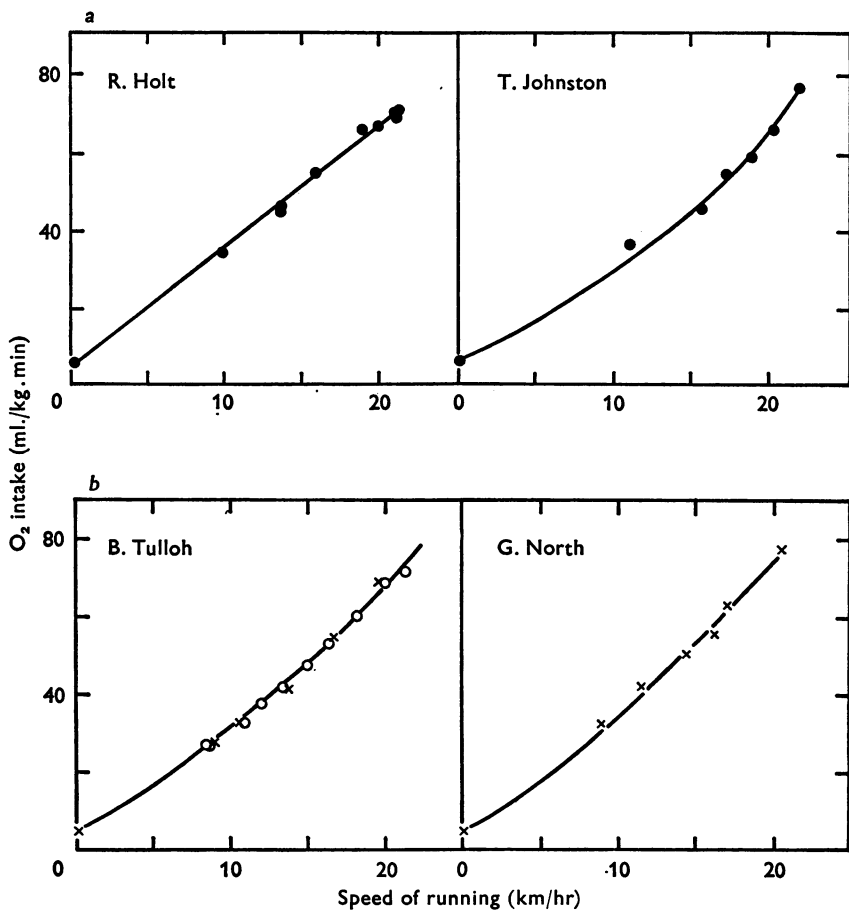$$\Delta\dot{V}_{O_2} = 0{\cdot}0089\ V^2, \tag{2}$$

Fig. 3. Relation of O_2 intake and speed in individual athletes (a) on the treadmill, and (b) on the track (B. Tulloh, × with shoes and ○ without shoes). The curves have been extrapolated to resting O_2 intake.

where $\Delta\dot{V}_{O_2}$ is the extra O_2 cost of running at a constant speed of 4·42 m/sec against wind of velocity V m/sec.

Air resistance on the running track. $\Delta\dot{V}_{O_2}$ is a measure of the power

TABLE 2. Track running. Lap times and O_2 intakes over the final mile run by each athlete are shown. The corresponding 3-mile times calculated from the average speeds over the last two laps are compared with each runner's best 3-mile performance in the same period. Also shown are some values of maximum O_2 intake from other experiments

Subject	Lap times (sec)	V_{O_2} last lap (ml./kg min)	Av. speed last 2 laps (km/hr)	Equivalent 3-mile time (min sec)	Best race time (min sec)	$V_{O_2,max}$ (ml./kg min)
M. H.	71·4					
	71·7					
	75·6					
	73·2	66·5	19·35	14 58·0	13 29	67·5*
M. T.	68·6					
	68·3					
	68·7					
	73·1	66·7	20·30	14 16·0	13 24	77·2
B. T.	71·0					
	70·0					
	63·1	71·4	21·16	13 41·2	13 12	—
B. T.	63·7					
	69·1					
	67·9					
	68·0	68·7	21·18	13 40·5	13 12	—
G. N.	75·3					
	69·1					
	68·7					
	66·0	76·6	21·38	13 32·8	13 29	77·8
G. N.	67·9					
	68·6					
	68·9					
	70·3	77·8	20·69	13 59·9	13 37	—
J. T.	70·6					
	69·3					
	69·9					
	69·0	62·3	20·73	13 58·3	13 36	—
T. J.	69·0					
	66·4					
	69·7					
	67·3	77·8	21·02	13 46·7	13 23	77·8
C. S.	67·0					
	66·4					
	71·6					
	62·4	73·7	21·62	13 24·2	8 49·4†	—

* Ergometer 5 min maximum exercise.
† 2-mile time. No 3-mile result available.

required to move the body at a speed S against a force F exerted by wind of velocity V, and since power equals force times velocity,
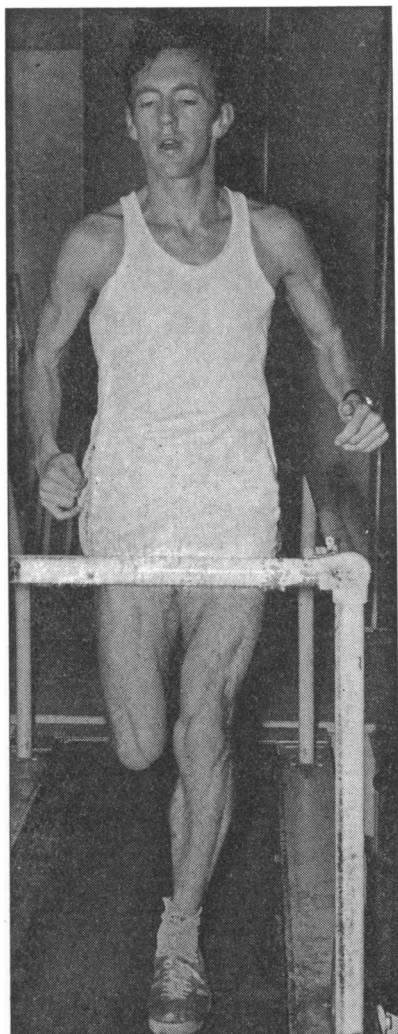
$$\Delta \dot{V}_{O_2} = aFS, \qquad (3)$$

Fig. 4. Photograph from which the athlete's projected area was determined in the experiment on the effects of air resistance. The reference surface of known area has been omitted.

where a is a proportionality constant depending on the units and the mechanical efficiency. But $F = bV^2$, as du Bois-Reymond (1925) and Hill (1927) showed, so that $\qquad \Delta \dot{V}_{O_2} = abSV^2.$ $\qquad (4)$

Eliminating $\Delta\dot{V}_{O_2}$ between eqns. (2) and (4), we get

$$abSV^2 = 0{\cdot}0089V^2;$$

hence

$$ab = \frac{0{\cdot}0089}{S}.$$

And since $S = 4{\cdot}42$ m/sec,

$$ab = \frac{0{\cdot}0089}{4{\cdot}42} = 0{\cdot}00201. \tag{5}$$

Therefore from (4), $\Delta\dot{V}_{O_2} = 0{\cdot}002\,SV^2$.

For an athlete of M. Turner's size (wt. 66·1 kg, A_p 0·478 m²) running on a track in calm air, V is the velocity of air movement relative to the body, and is equal to the running speed S: consequently,

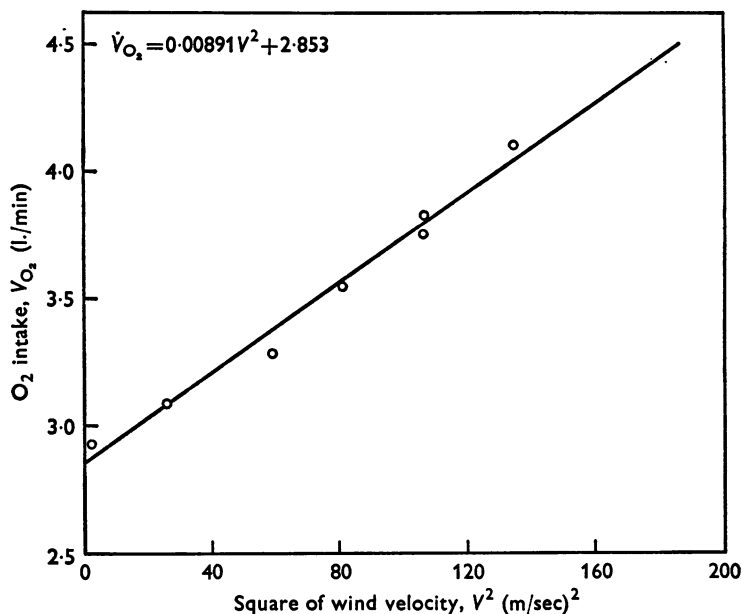$$\Delta\dot{V}_{O_2} = 0{\cdot}002\,V^3. \tag{6}$$

Fig. 5. O_2 intake plotted against the square of wind velocity for M. Turner running at 15·9 km/hr (4·42 m/sec) against wind of varying velocity.

For an athlete of projected area A_p m², eqn. (6) becomes

$$\Delta\dot{V}_{O_2} = \frac{A_p}{0{\cdot}478} \times 0{\cdot}002\,V^3$$

$$= 0{\cdot}00418\,A_p\,V^3, \tag{7}$$

where $\Delta\dot{V}_{O_2}$ is in l./min, and V is in m/sec.

From eqn. (7) we calculated the O_2 cost of overcoming air resistance in the track experiments at Motspur Park and Twickenham. The mean projected area of the runners calculated as surface area $\times$ 0·266 was 0·436 m², and at a speed of 21·5 km/hr (6·0 m/sec)

$$\Delta \dot{V}_{O_2} = 0·436 \times 0·00418 \times (6·0)^3$$

$$= 0·394 \text{ l./min.}$$

The mean wt. was 61·3 kg so that this represents 6·4 ml./kg.min. The observed values for running on the track and the treadmill at this speed were 74·6 and 68·3 ml./kg.min respectively; the difference was 6·3 ml./kg.min.

Statistical treatment. In order to examine the question whether the slopes of the lines for treadmill running and track running were significantly different, separate lines were fitted for each subject, and the mean of the two sets of lines were compared by Students' t test. The mean slopes, which were 3·0550 (S.E. $\pm$ 0·154) for the treadmill runners and 3·531 (S.E. $\pm$ 0·093) for the track runners, were significantly different at the 5 % level. The slopes of the lines fitted to the pooled data which are shown in Figs. 2 and 1 were 2·979 and 3·656 respectively.

DISCUSSION

According to the above results the relation of $\dot{V}_{O_2}$ and speed in track running at speeds between 8 km/hr (2·2 m/sec) and 21·5 km/hr (6·0 m/sec) can be described, for practical purposes, by a straight line having a somewhat steeper slope than the corresponding line for the treadmill results. In track running, unlike treadmill running or ergometer exercise, the zero intercept of the $\dot{V}_{O_2}$/speed line does not coincide with resting $\dot{V}_{O_2}$, the reason being that the physiological relation is, in fact, non-linear owing to the effect on $\dot{V}_{O_2}$ of air resistance, which increases as the cube of the runner's speed. It was not possible to demonstrate this convincingly by direct experiment because non-linear graphs were obtained both on the treadmill and on the running track in some experiments. M. Turner suggested the explanation might lie in changes of style with increase of speed.

The graph of $\dot{V}_{O_2}$ and speed in Fig. 1 is intended as a practical means of estimating energy expenditure from running speed. It was considered that the main source of variation was the ratio of muscle-mass to body weight, since differences in physique were obvious. All the athletes were thin, having mean skinfold thicknesses of 3·7–5·7 mm. There was some increase in scatter at high running speeds owing to uneven running over successive laps (Table 2). Variation due to the nature of the track or the type of footwear seems to have been small. The highest speed observed, which was

21·5 km/hr (6·0 m/sec), was equivalent to running a 3-mile race in 13 min 36 sec; this was well within the capacity of all these athletes (Table 2). The contribution of anaerobic energy, therefore, is likely to have been small and $\dot{V}_{O_2}$ has been taken as a measure of the energy cost of the exercise.

The method of estimating the energy cost of overcoming air resistance in track running from data obtained on a treadmill is open to the objection that the air-flow over the surface of the body of an athlete running on a track in calm air may not be the same as the air-flow in a climatic chamber. It is known that the drag coefficient of bodies towed in calm air is similar to that determined in well designed wind tunnels (Schlichting, 1968). However, turbulence of the air stream in a wind tunnel may affect results to some extent even at subcritical Reynold's numbers, and it is possible the results obtained at the I.A.M. chamber are a little high. Further research into this matter is in progress.

TABLE 3. Results of athletic events at the Olympic Games, Mexico City, 1968, compared with existing world records (October 1968) and record times at sea-level (National Union of Track Statisticians)

Distance (m)	Olympic finals (min sec)		World record (min sec)		Sea-level best performance (min sec)		% differences from sea-level best performance
100		9·9		9·9		10·0	+1·0
200		19·8		19·7		20·0	+1·0
400		43·8		43·8		44·5	+1·6
800	1	44·3	1	44·3	1	44·3	0
1,500	3	34·9	3	33·1	3	33·1	−0·8
5,000	14	05·0	13	16·6	13	16·6	−6·1
10,000	29	27·4	27	39·4	27	39·4	−6·5

In comparing track and treadmill results, the energy cost of running round the curves on a running track should be considered as well as the effect of air resistance. I am aware of no direct measurements of this but B. B. Lloyd (personal communication, 1966) concludes the effect at 6 m/sec is negligible. It would seem, therefore, that air resistance accounts for about 8 % of the net energy cost of track running at middle distance speeds. For running at a mean speed of 36 km/hr (10·0 m/sec), which is the average speed in a world class 100 m sprint, $\Delta \dot{V}_{O_2}$ from eqn. (6) is 2·0 l./min for a man of Turner's size, and the energy cost of overcoming air resistance works out at 1667 cal over 100 m. From the known sources of energy available to the body, Margaria (1968) has estimated the energy used in a 100 m sprint to be about 160 cal/kg, which, for M. Turner, amounts to

10,400 cal: according to this estimate the wind resistance component may be about 16 % of the total energy expended.

The effect of air resistance is of special interest in connexion with the Olympic Games in Mexico City (2270 m: barometric pressure 580 mm Hg) since air resistance is proportional to air density and air density varies directly with barometric pressure. At the time of the Games the barometric pressure was 23·5 % lower than the sea level value. In the middle distance events, therefore, there should have been an $8·0 \times 0·235 = 1·9$ % reduction in the net energy cost of running as a result of reduced air resistance to offset the effect of hypoxia. The times in the 5000 m and 10,000 m events were respectively 6·1 and 6·5 % slower than sea level world records (Table 3). A similar result was reported by Pugh (1967) on a party of British athletes in Mexico City in 1965. The British athletes ran 5·8 % more slowly in 3-mile trials at altitude than in control races in England, while the reduction of $\dot{V}_{O_2, max}$ in ergometer exercise was 7·9 % in the four best adapters.

The effect of altitude on sprinting is more complex. In the 100 m event the reduction in the air resistance was of the order of 4 %, but the apparent gain in mean speed was only 1 %. However, Lloyd (1967) in his mathematical analysis of athletic events predicted an improvement of 0·13 sec in the 100 m event in the Mexico Olympic Games. His analysis implies that something like half the energy is aerobic and, therefore, influenced by arterial unsaturation.

In cycling events in Mexico City, world records were broken in team and individual races lasting over 4 min as well as in shorter events (Phillips, 1969). At the high speeds maintained in cycling (viz. 52 km/hr over 4000 m) the gain from reduced air resistance evidently outweighed the effect of hypoxia not only over short distances, but also in sustained exercise depending on concurrently absorbed oxygen.

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